What does it take to discover or falsify Weak Scale SUSY?

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Keith is one of the great practitioners of SUSY phenomenology

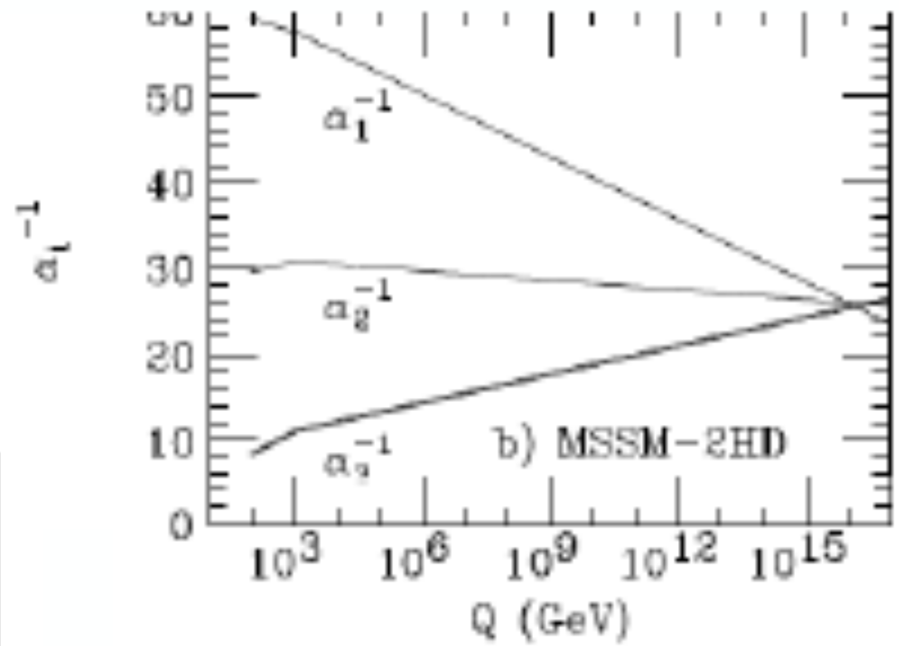
Please see: ScienceWatch determination
of top authors on SUSY from 2011-
includes interview with Keith!
http://archive.sciencewatch.com/ana/st/super/authors/

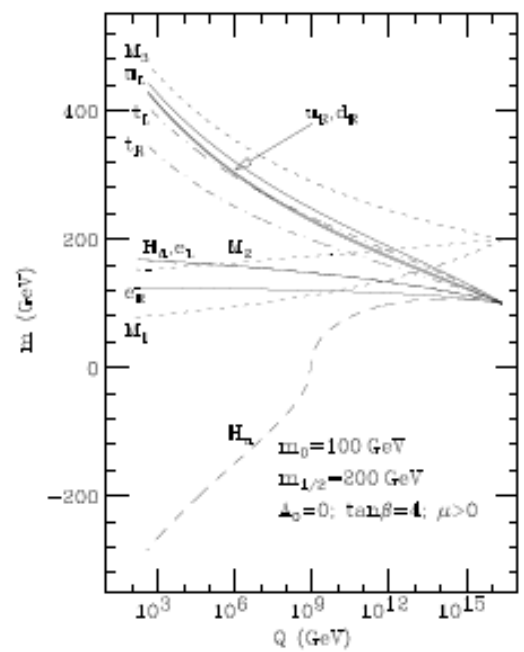
Papers

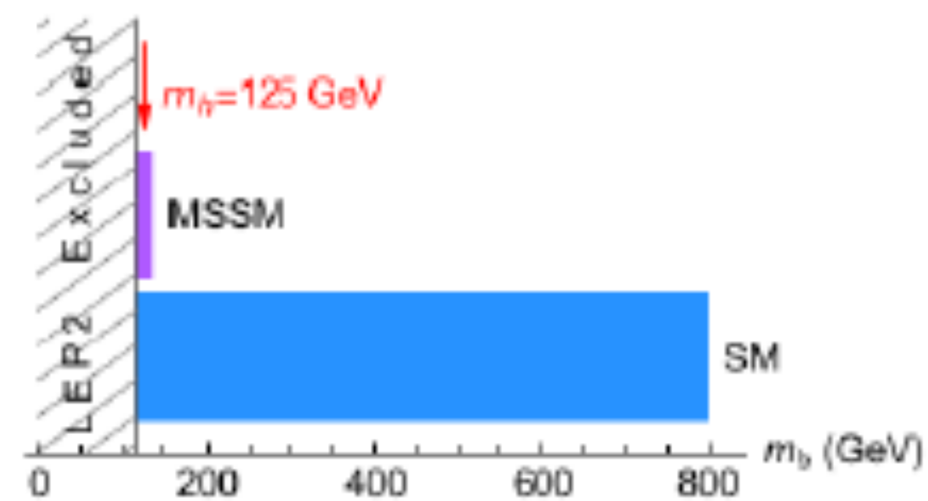
Rank	Author	Citations	Papers	Cites per paper
1	Ellis, J **Special Topics Interview**	4,632	134	34.57
2	King, SF	1,917	96	19.97
3	Heinemeyer, S **Special Topics Interview**	3,135	88	35.63
4	Olive, KA **Special Topics Interview**	3,792	85	44.61
5	Porod, W	2,576	84	30.67

MSSM actually supported (indirectly) via data!

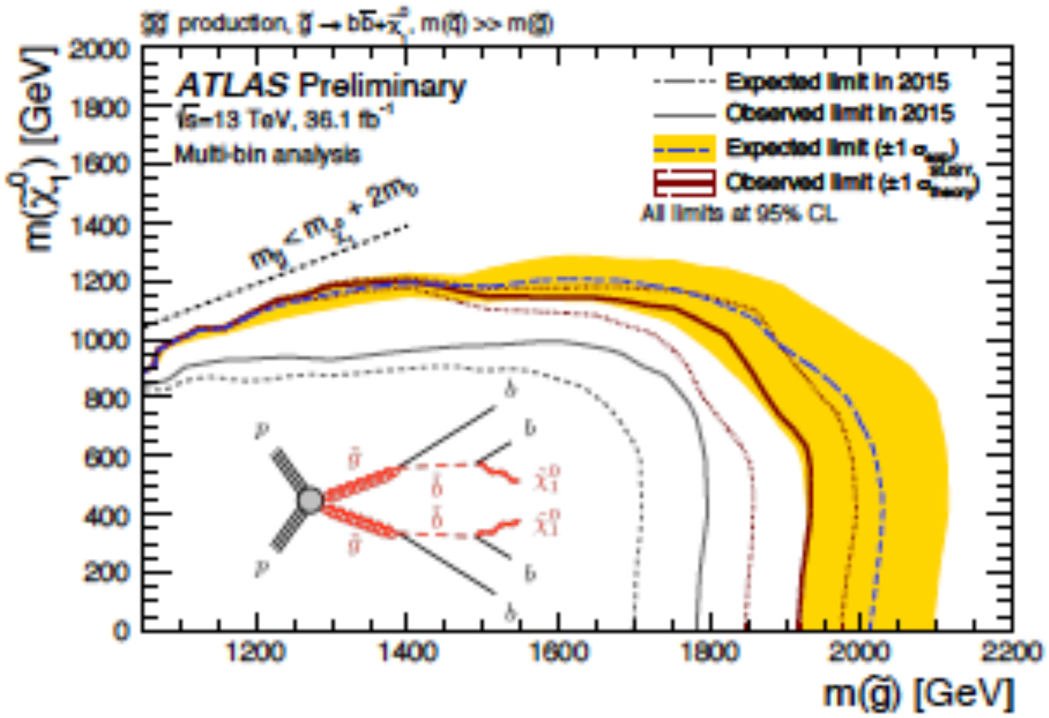
- stabilize Higgs mass
- measured gauge couplings
- m(t)~173 GeV for REWSB
- mh(125): squarely within narrow SUSY window



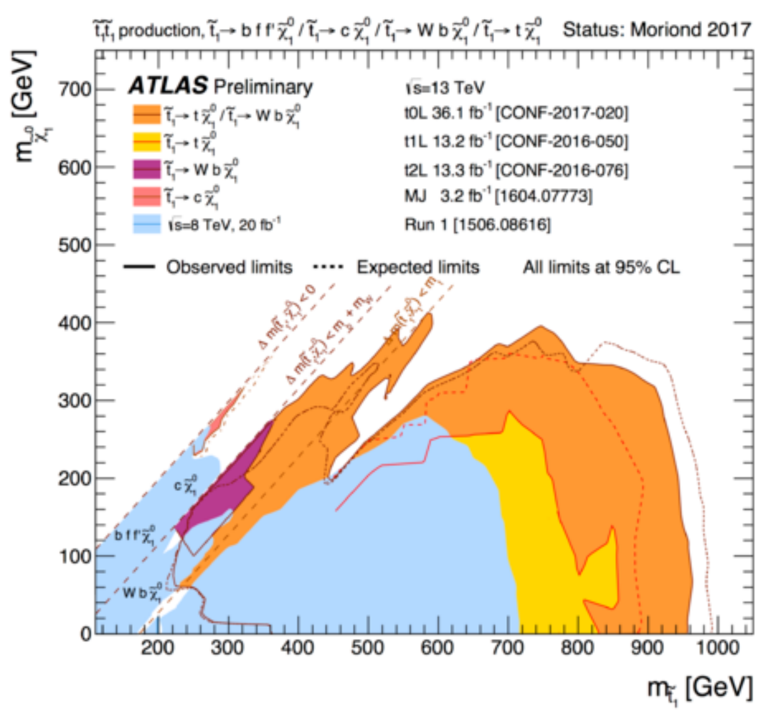




But so far, no SUSY seen at LHC



Evidently $m_{\tilde{g}} >\sim 2$ TeV
compare to BG(1987) upper bound $m_{\tilde{g}} < 0.35$ TeV

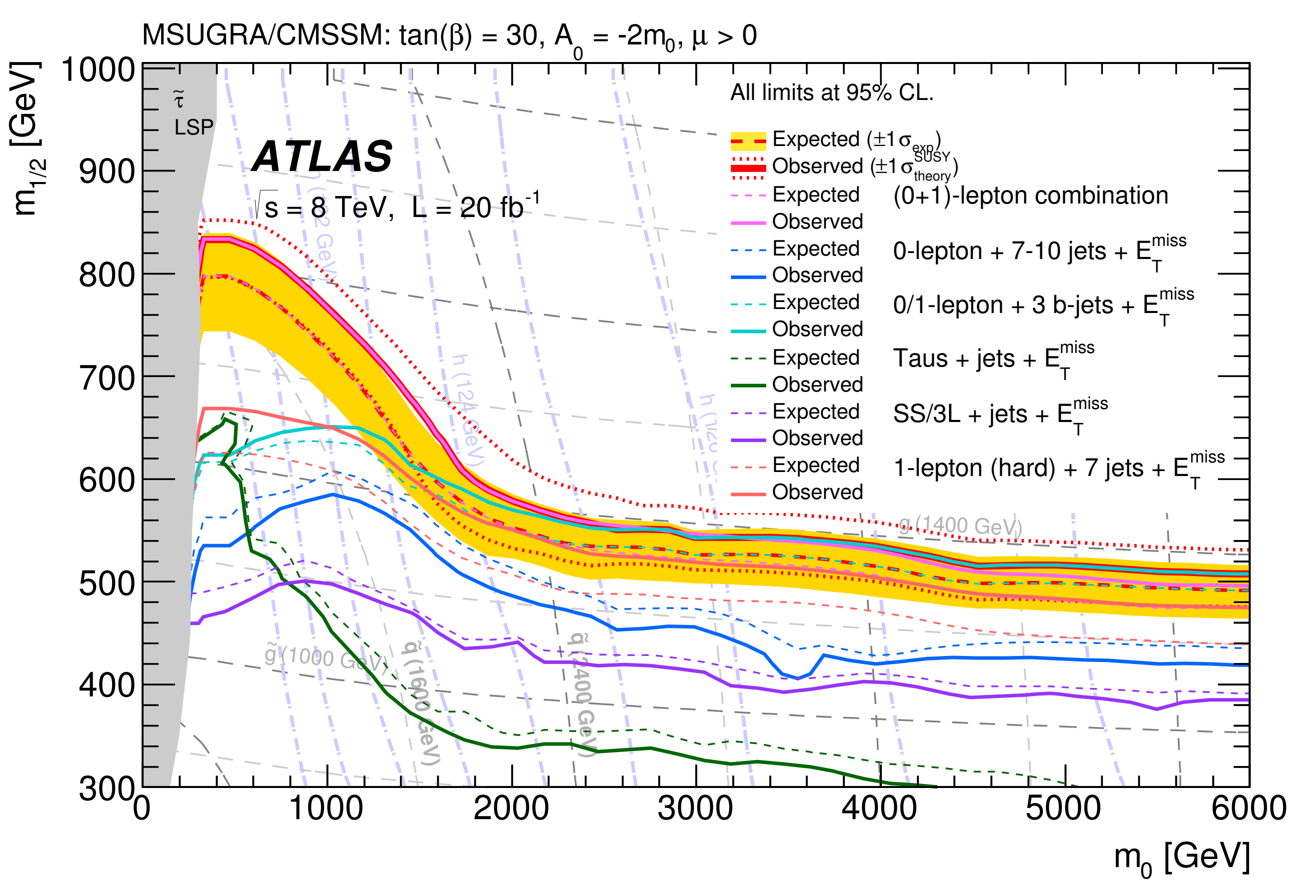


No 3 third generation squarks < 0.5 TeV

Is it time for Keith (and others of us) to stop searching for SUSY and move on to something else?

- Does SUSY parameter space go on forever?
- When are we done searching for SUSY?
- What does it take to discover or falsify Weak Scale SUSY?

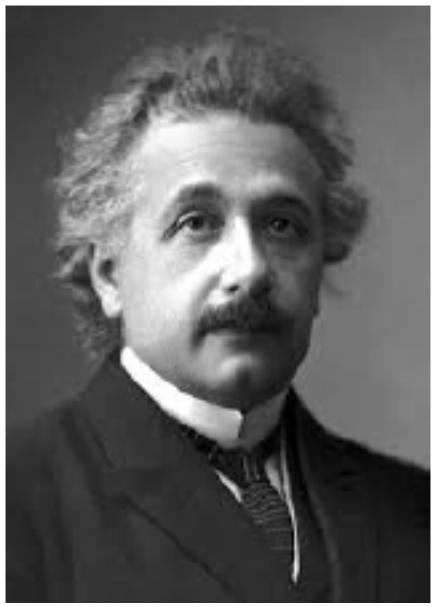
go this way?



Do WIMPs provide upper limit to p-space?

- Not much room left by LHC for thermal WIMPs
- WIMP -> gravitino (super-WIMP)?
- WIMP -> axino as LSP?
- WIMP -> SM particles (R-parity violation)?
- entropy dilution by late decaying BB relics?

Motivation: simplicity and naturalness



``Everything should be made as simple as possible, but not simpler"

A. Einstein

``The appearance of fine-tuning in a scientific theory is like a cry of distress from nature, complaining that something needs to be better explained"

S. Weinberg

Historically, naturalness has been a reliable guide to new physics and is the main motivation for WS-SUSY

An observable $\mathcal{O}$ is natural if each independent contribution to $\mathcal{O}$ is comparable to or less than $\mathcal{O}$.

- mass of electron=> QED
- KL-KS mass difference and m(charm)

Apply to SM m(Higgs):

$$m_{H_{SM}}^2 = 2\mu^2 + \frac{3}{4\pi^2}\left(-\lambda_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_W} + \lambda\right)\Lambda^2$$

Evidently $\Lambda <\sim 1$ TeV

Do latest LHC sparticle mass limits and m(h) make SUSY also unnatural?

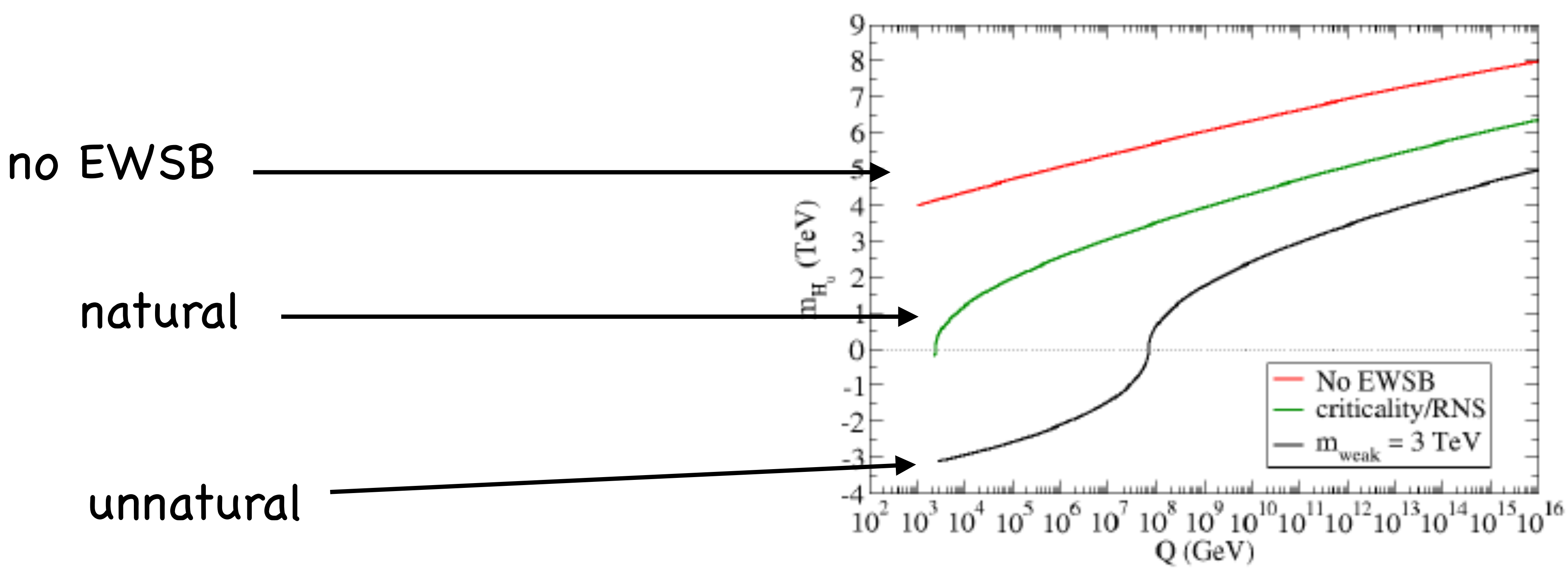
``…settling the ultimate fate of naturalness is perhaps the most profound theoretical question of our time''

Arkani-Hamed et al.,
arXiv:1511.06495

``Given the magnitude of the stakes involved,
it is vital to get a clear verdict on naturalness from experiment''

This should be matched by theoretical scrutiny of what we mean by naturalness

- In MSSM, then $m_h^2 \simeq m_{H_u}^2 + \mu^2 + mixing + rad.cor.$
- then $\mu \sim m_h$
- and $|m_{H_u}^2| \sim -m_h^2$



Alternatively, relating m(Z) to Lagrangian parameters is more constraining:

Most direct expression within MSSM:
minimize scalar potential to determine VeVs:
relate measured value of m(Z) to weak scale SUSY Lagrangian

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

weak scale soft term:

radiative corrections: biggest from t1,t2

SUSY conserving mu term

no large unnatural cancellations:
all terms on RHS are <~100-200 GeV

$$\Delta_{\rm EW} \equiv \max|\text{each additive term on RHS}|/(m_Z^2/2)$$

$$m_Z^2/2 = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \sim -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

naturalness: no large unnatural cancellations on RHS

then:

- $\mu \sim 100 - 200$ GeV
- $m_{H_u}^2$ can be driven to natural via large top Yukawa
- radiative corrections not too large

naturalness: only higgsinos need be ~100-200 GeV

higgsino is LSP

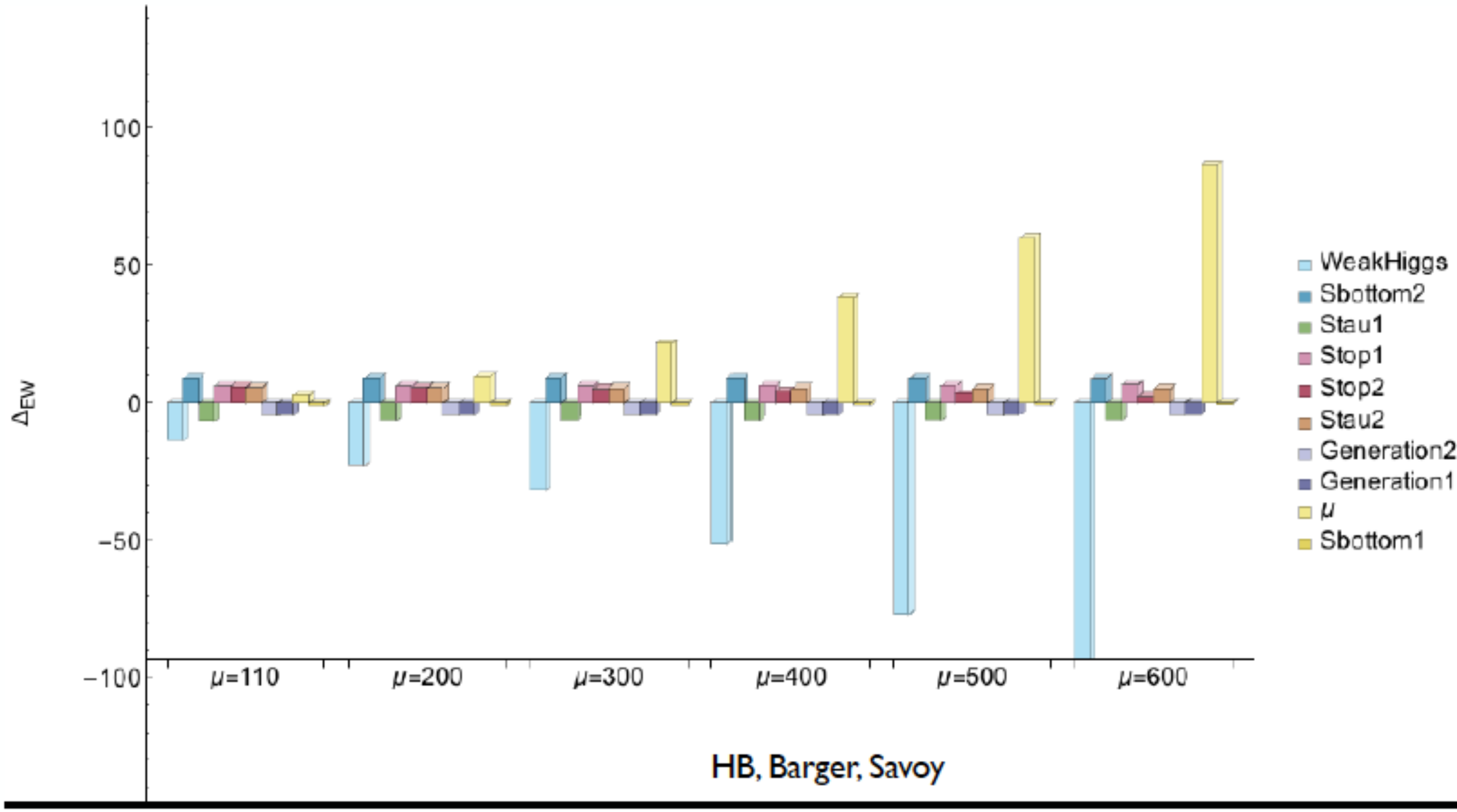
higgsino-like WIMP~100-200 GeV thermally underproduced as DM

- Δ_{EW} is most conservative: $\Delta_{EW} < \Delta_{EENZ/BG} < \Delta_{HS}$
- Δ_{EW} model independent: for given spectra, same for pMSSM as for CMSSM
- $\Delta_{EENZ/BG} = max_i|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}|$ usually evaluated in artificial multi-parameter effective theories; in fundamental theory where all soft parameters all correlated *e.g.* SUGRA where $m_{soft} = a \cdot m_{3/2}$, then $\Delta_{EENZ/BG} \simeq \Delta_{EW}$
- $\Delta_{HS} \equiv \delta m_h^2/m_h^2$ cherry-picks top-squark fluctuation out of variety of intertwined contributions; using RGE, then $\Delta_{HS} \simeq \Delta_{EW}$

light 3rd gen. squarks with m<0.5 TeV
***not* required for naturalness**

$$\Sigma_u^u(\tilde{t}_{1,2}) < 30 \Rightarrow m_{\tilde{t}_1} <\sim 3 \text{ TeV}$$

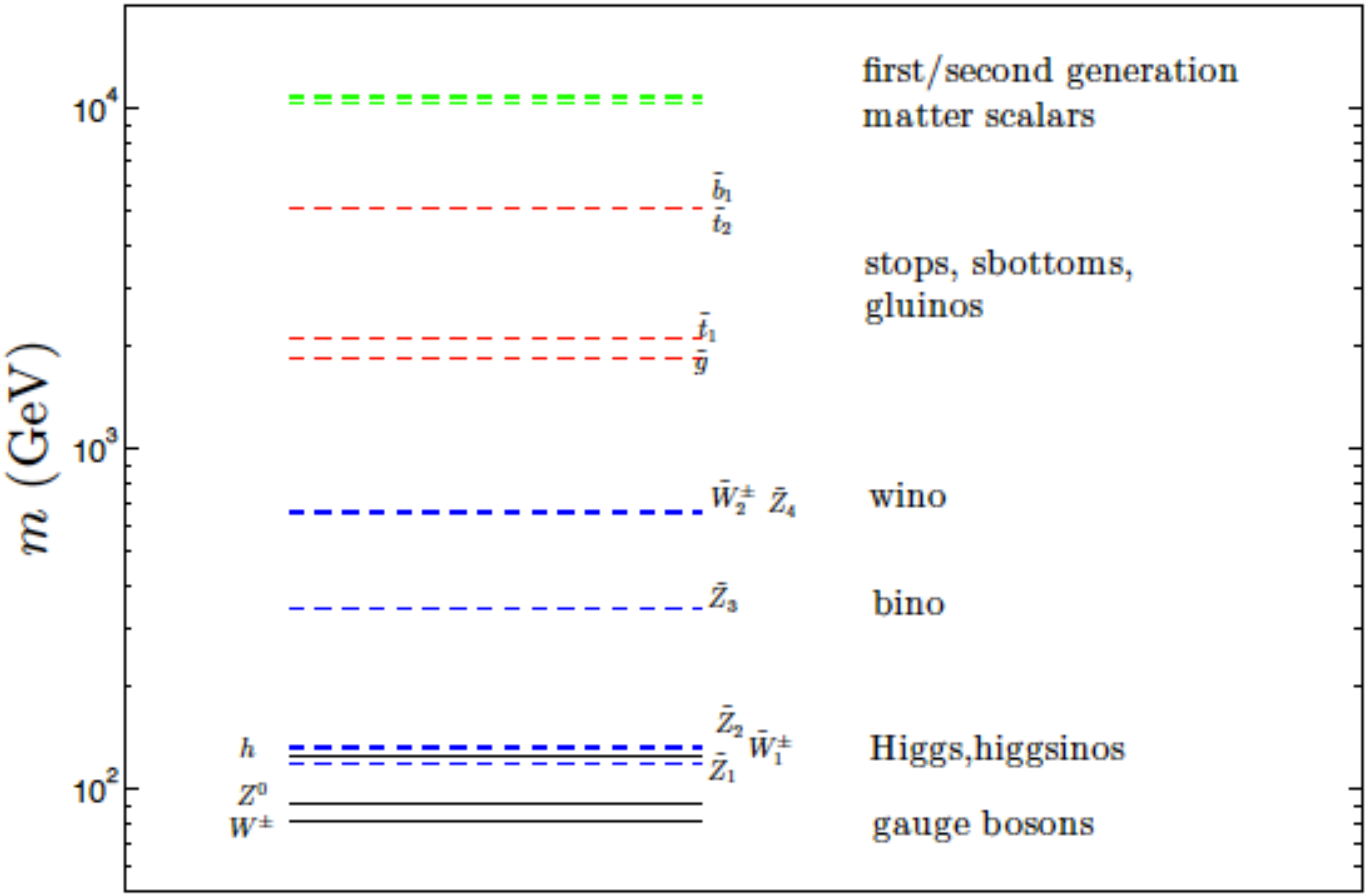
How much is too much fine-tuning?



Visually, large fine-tuning has already developed by $\mu \sim 350$ or $\Delta_{EW} \sim 30$

higgsinos should be accessible to ILC!

Typical spectrum for low Δ_{EW} models

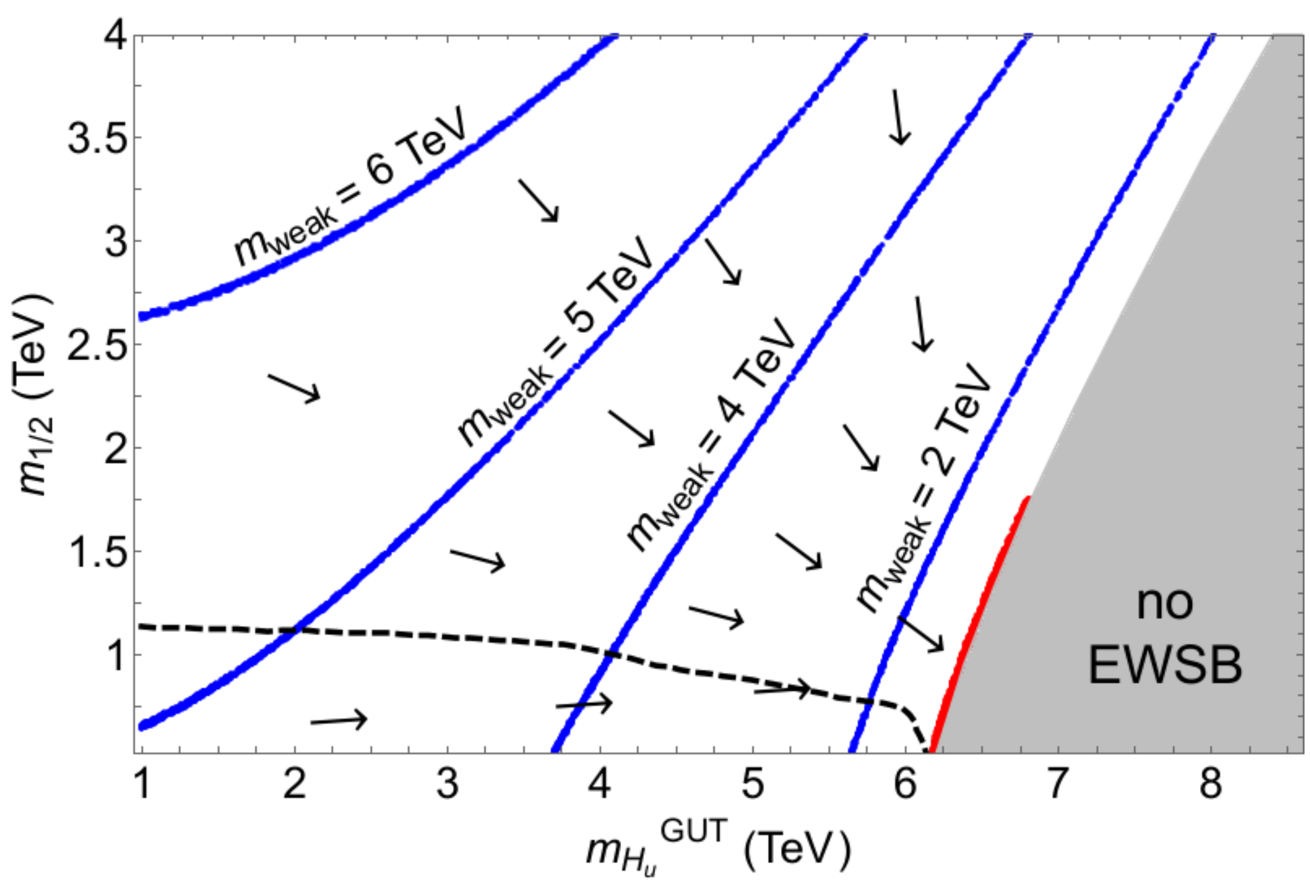


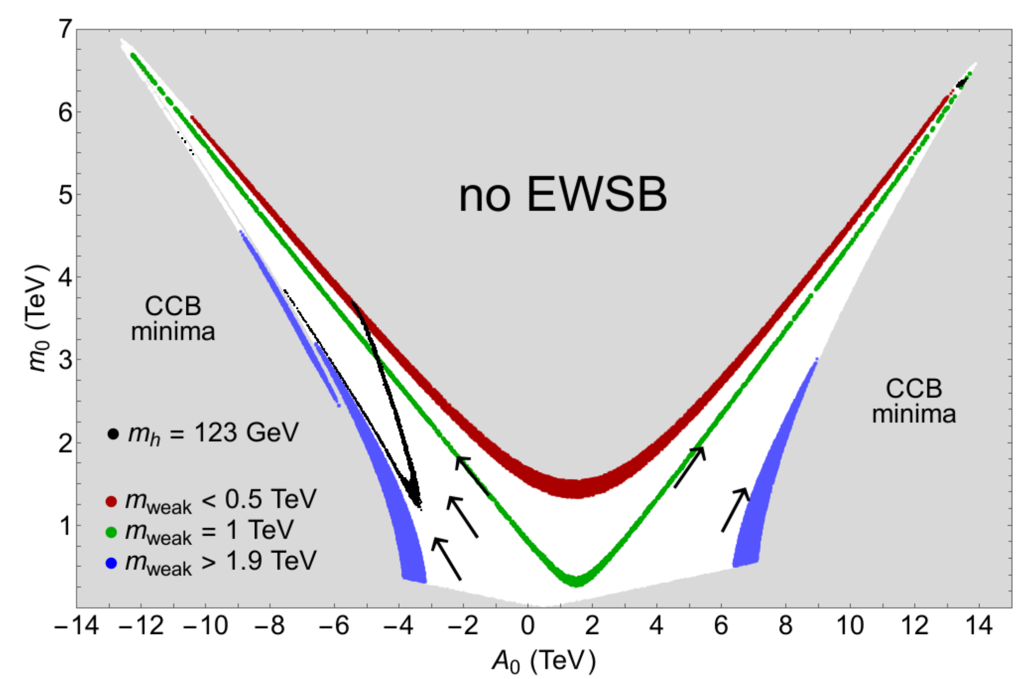
There is a Little Hierarchy, but it is no problem

$$\mu \ll m_{3/2}$$

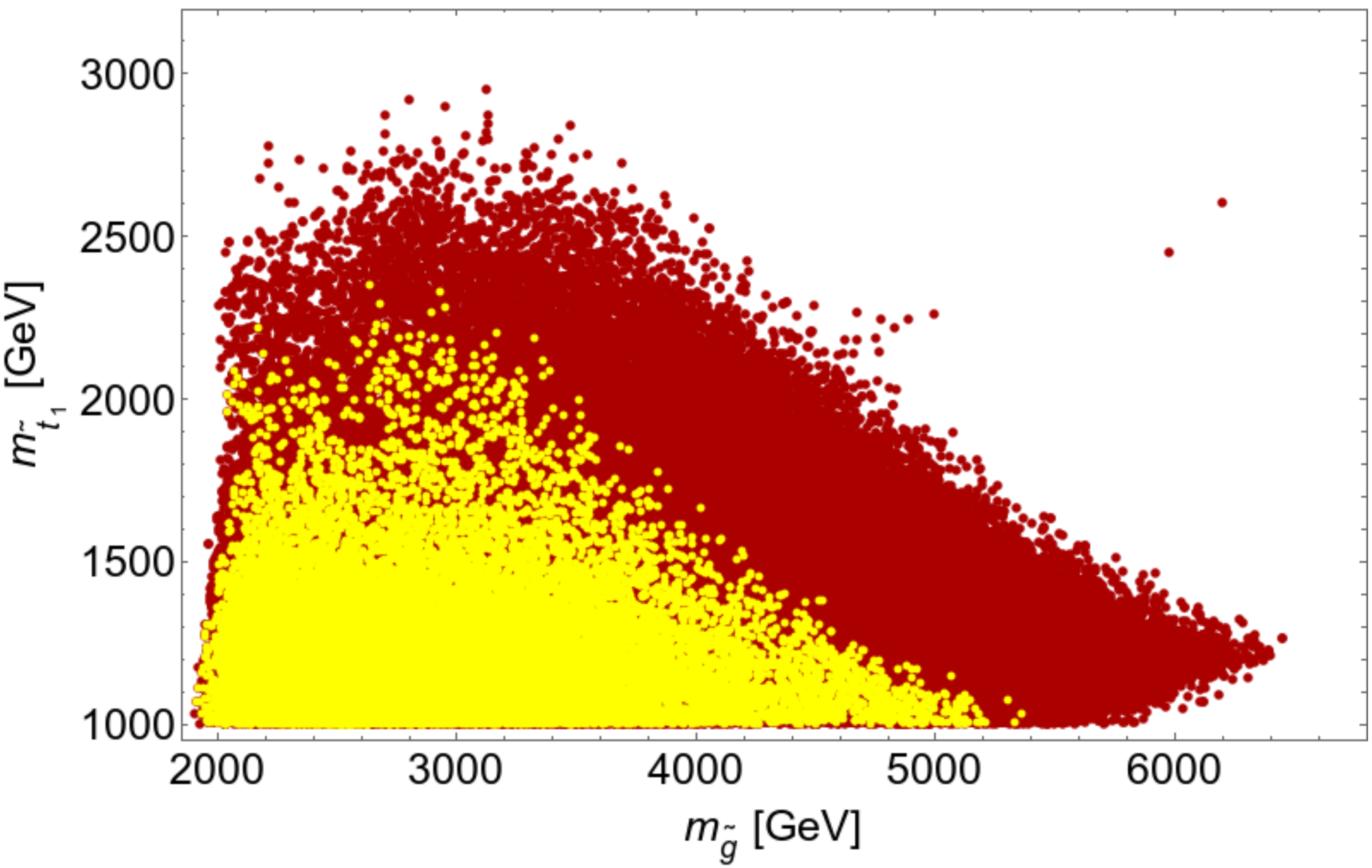
Why should nature choose natural SUSY soft terms?
Weinberg: CC as big as possible to allow habitable universe

nSUSY: soft terms statistically drawn to large values
but such as to yield a weak scale ~100 GeV:
landscape+anthropics!





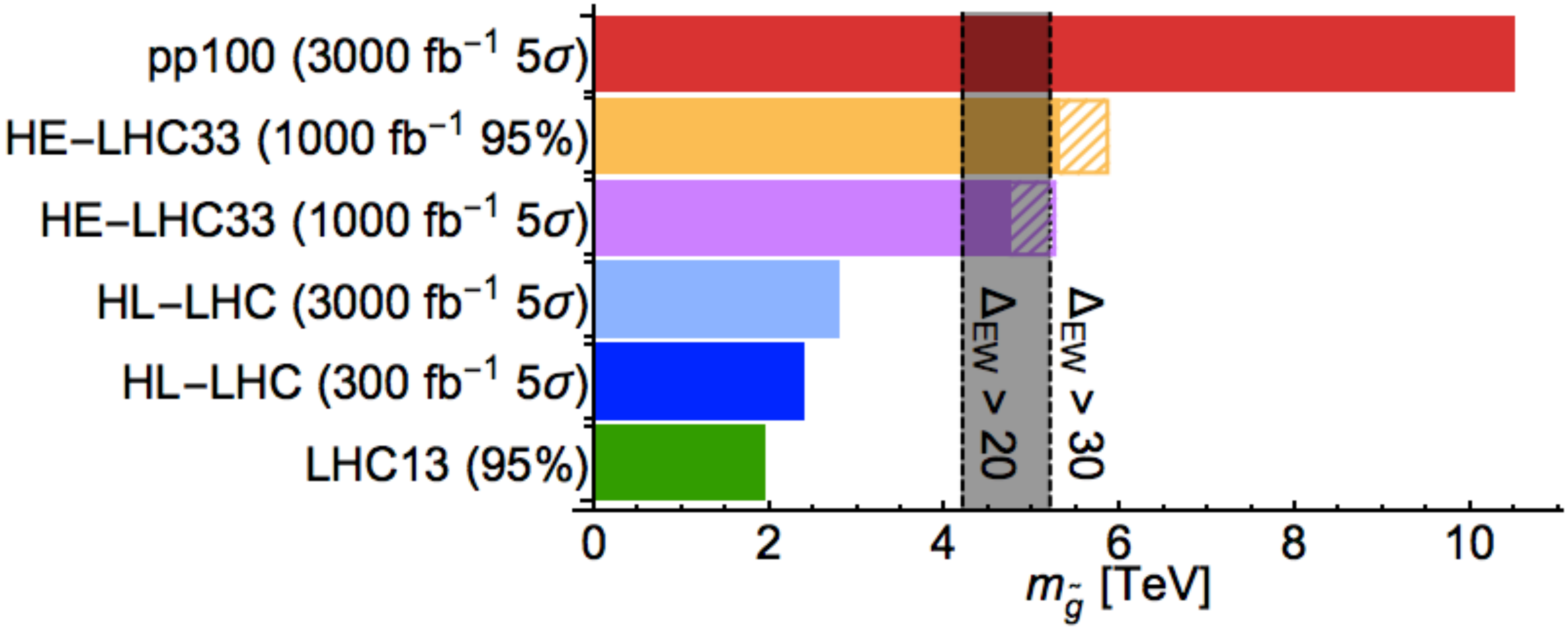
For $\Delta_{EW} < 20$ (30), can find reliable upper limits on $m(sparticle)$ from scans



For NUHM3 model with $m_0(1,2) = 20$ TeV then

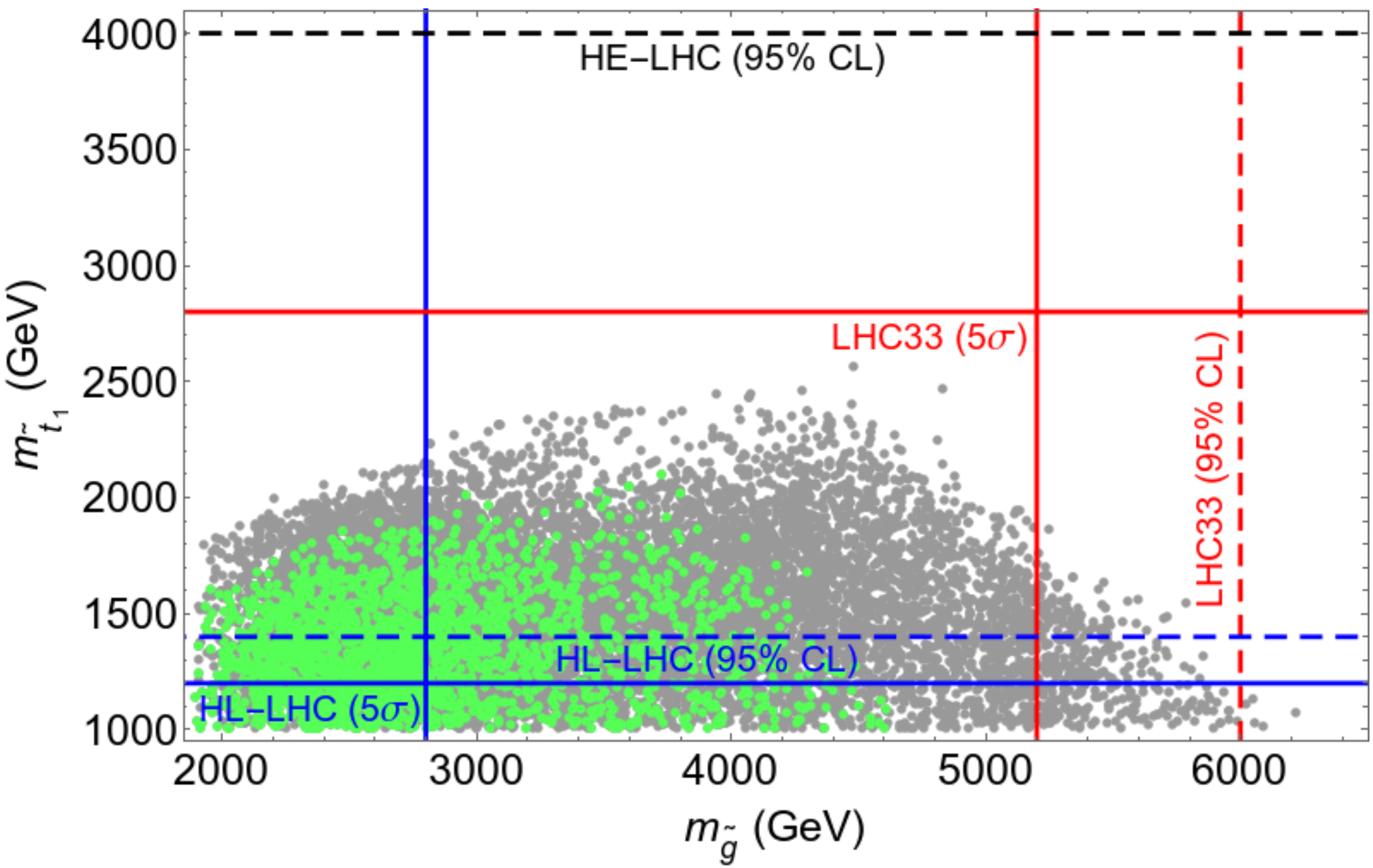
- $m_{\tilde{g}} <\sim 5-6$ TeV
- $m_{\tilde{t}_1} <\sim 2-3$ TeV

Compare naturalness upper bound to
reach of current/future colliders



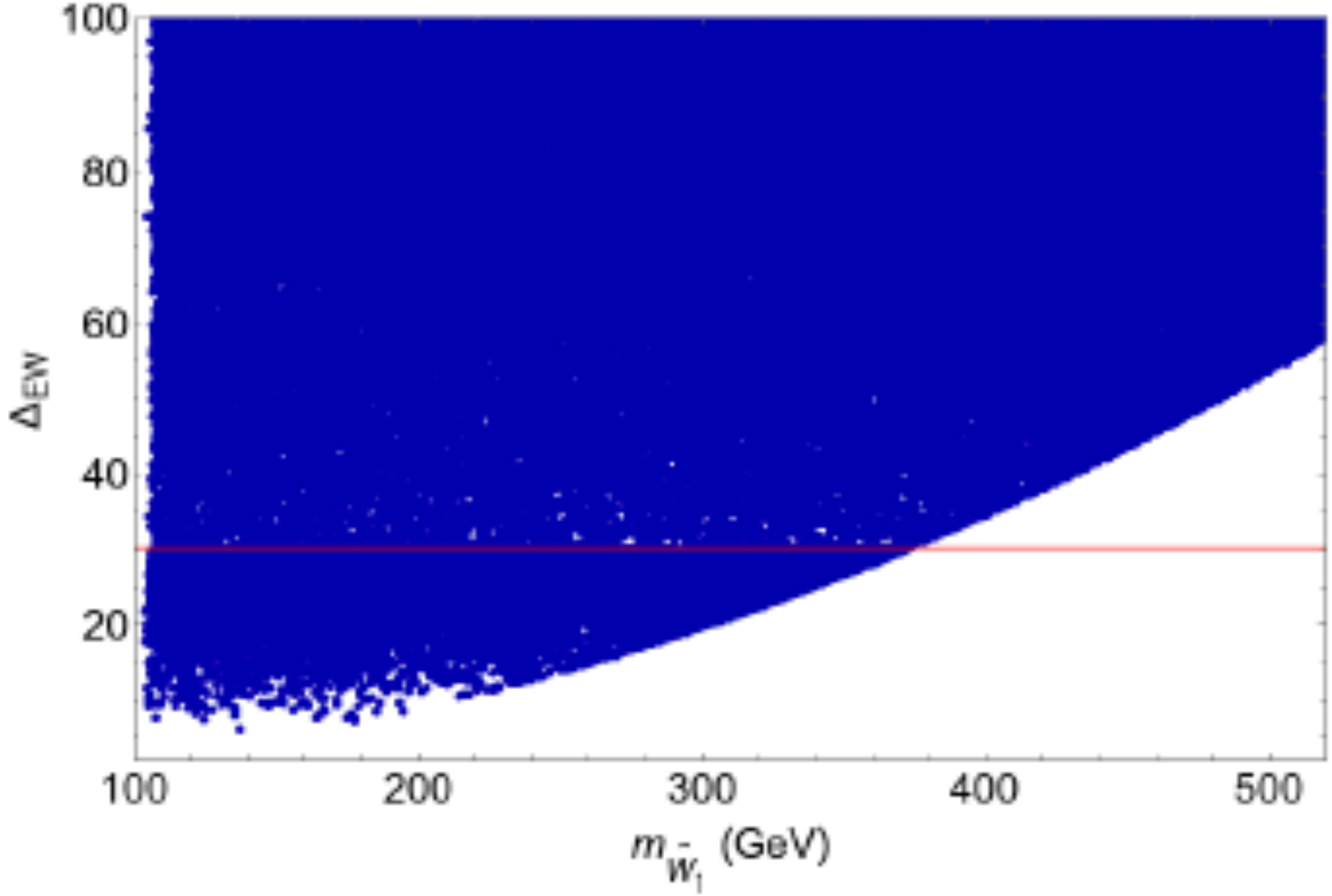
Note to CERN council:
LHC33 needed to cover natSUSY p-space!

LHC33 needed to cover $\tilde{t}_1\tilde{t}_1^*$ and $\tilde{g}\tilde{g}$ search channels



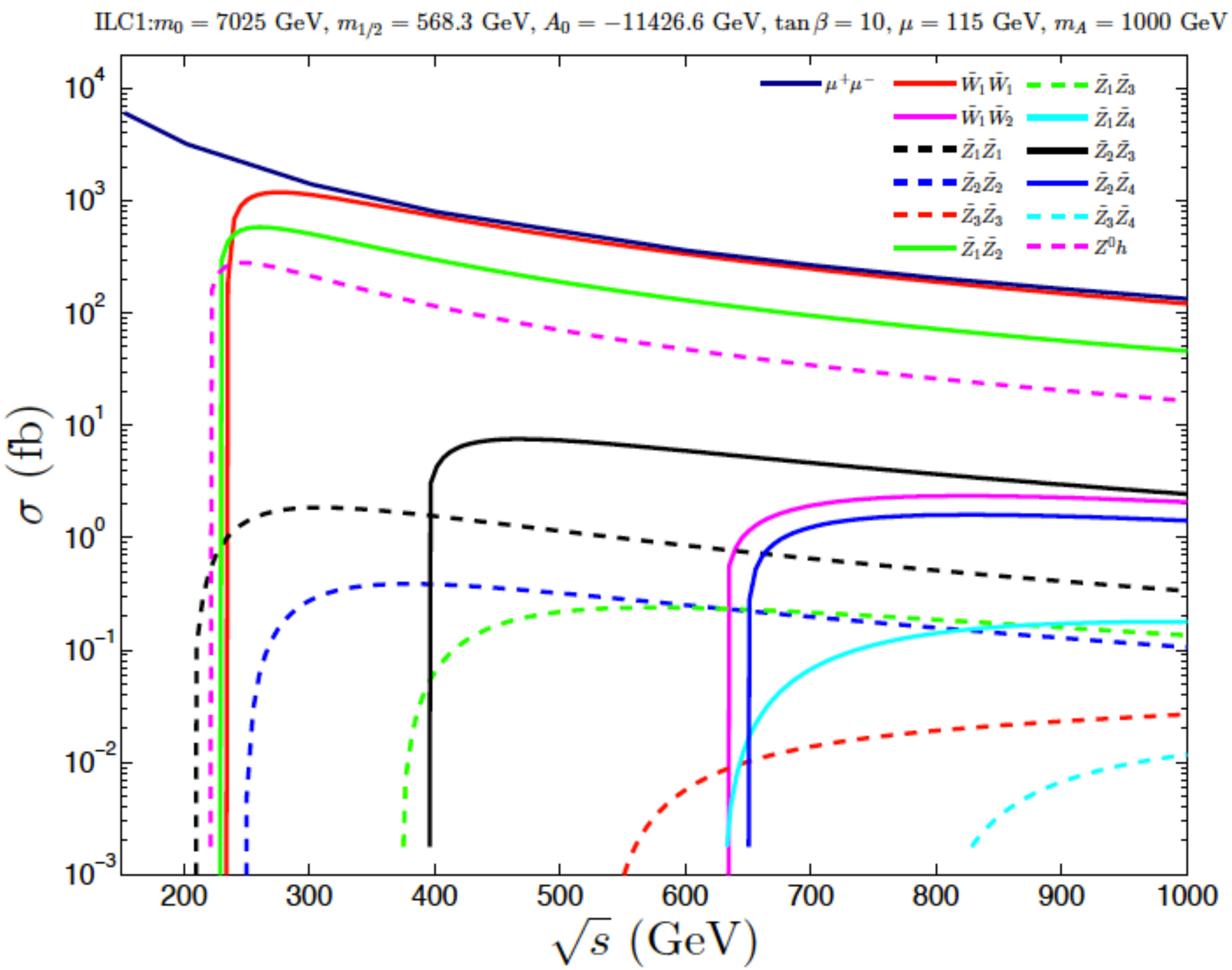
natural generalized mirage mediation~
Ellis, Olive, Sandick subGUT models

Higgsino-like lightest EWinos < 300-350 GeV



Compressed mass=>
hard to see at LHC but easy at ILC

ILC is Higgs/higgsino factory!

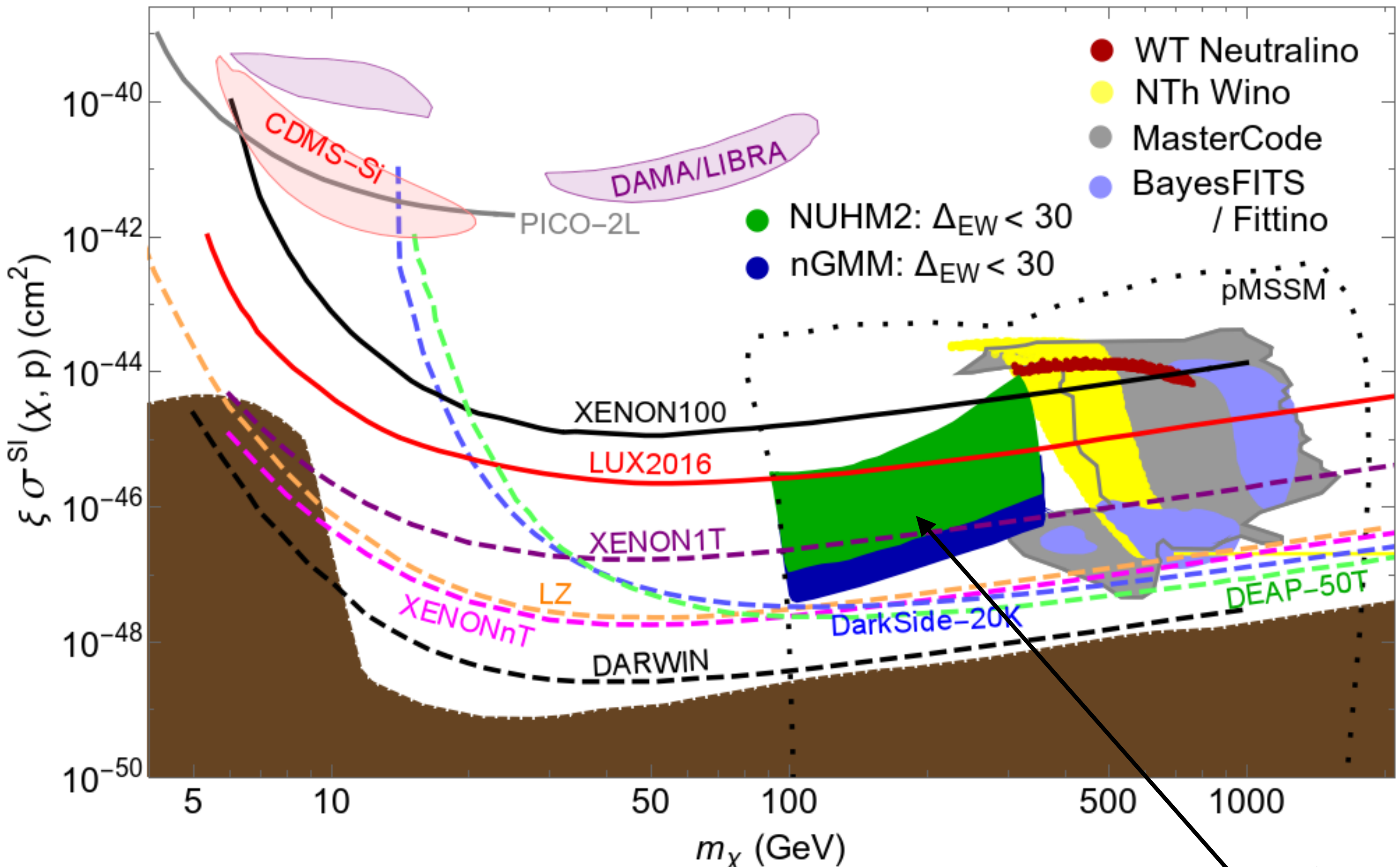


$$\sigma(higgsino) \gg \sigma(Zh)$$

10–15 GeV higgsino mass gaps no problem in clean ILC environment

HB, Barger, Mickelson, Mustafayev, Tata
arXiv:1404:7510

Direct higgsino detection rescaled for minimal local abundance $\xi \equiv \Omega_\chi^{TP} h^2/0.12$



natural SUSY

Bae, HB, Barger, Savoy, Serce

$$\mathcal{L} \ni -X_{11}^h \overline{\widetilde{Z}}_1 \widetilde{Z}_1 h$$

$$X_{11}^h = -\frac{1}{2}\left(v_2^{(1)} \sin\alpha - v_1^{(1)} \cos\alpha\right)\left(g v_3^{(1)} - g' v_4^{(1)}\right)$$

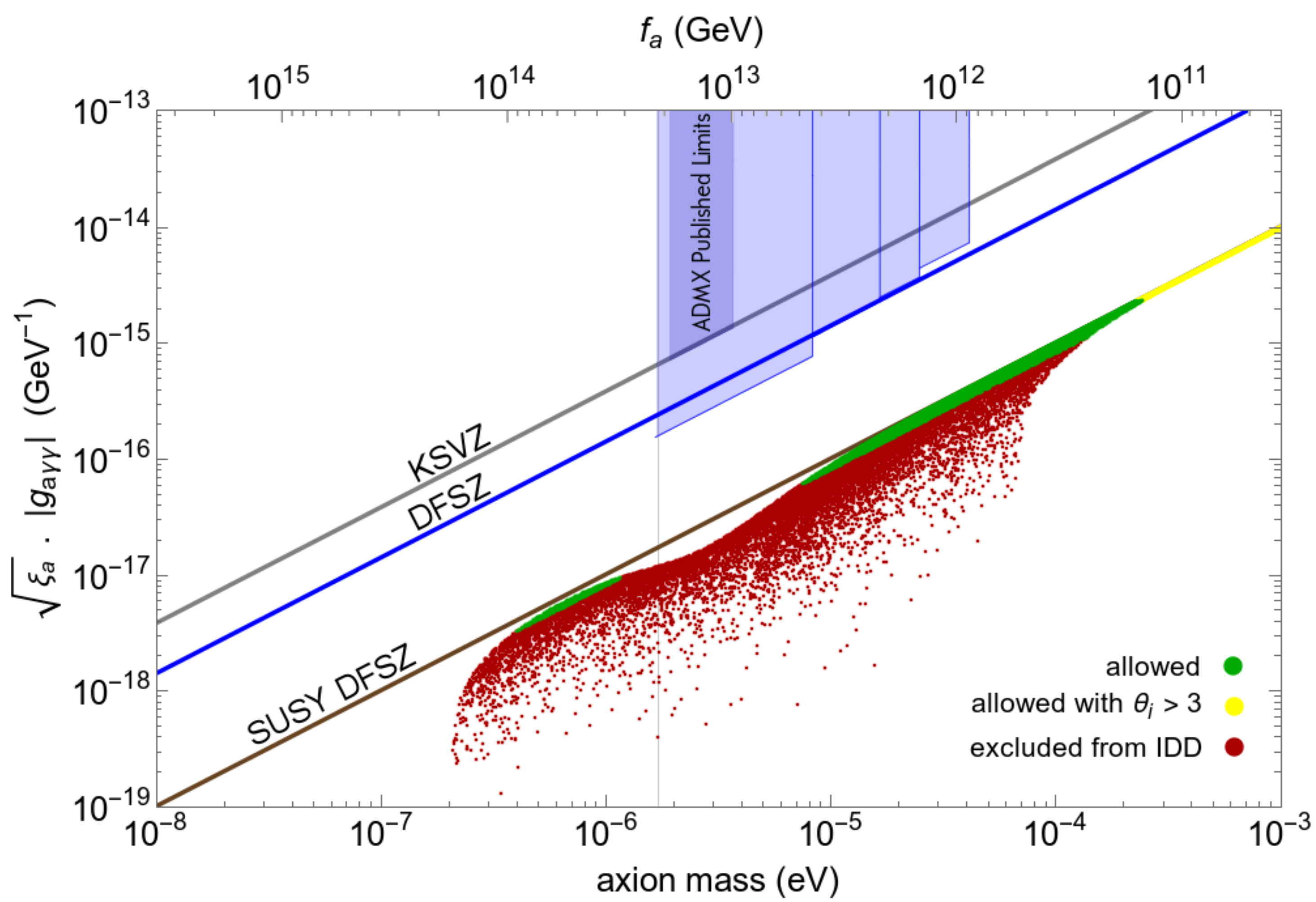
Xe-1-ton
now operating!

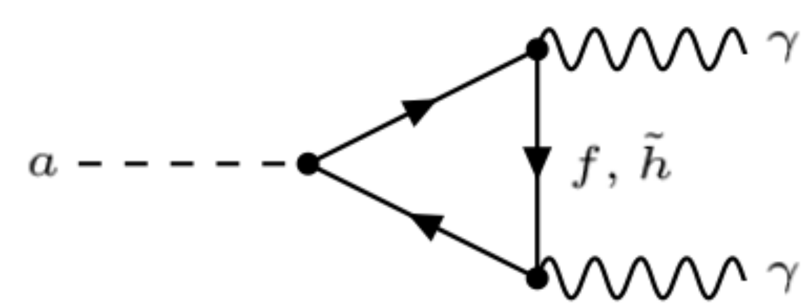
Can test completely with ton scale detector or equivalent (subject to minor caveats)

If light higgsinos make up some of DM,
perhaps axions make up the rest?

DFSZ SUSY axion model: solves strong CP problem, SUSY mu problem and allows for Little Hierarchy where mu~f_a^2/mP while m(SUSY)~m(hidden)^2/mP

m(Higgs) ~mu tells us where to look for axion





Conclusions:

- naturalness -> upper bounds on sparticle masses
- when to give up on SUSY?
- no WIMPs at Xe-n-ton/LZ
- no higgsinos at ILC
- no gluinos/top-squarks at LHC33

I have for long been inspired by Keith’s work on SUSY:
contrary to much of contemporary opinion,
we SUSY-philes have a long way to go!